Coherent Radio emission, PSG model and Drifting subpulses

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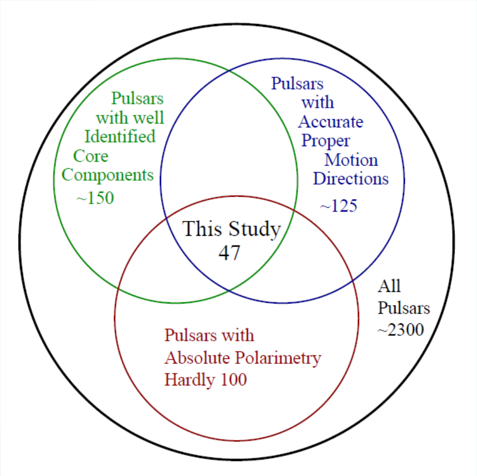
Observational facts:

1. The radio emission mast be generated by a coherent mechanism.
2. The radio emission is generated at the altitudes about 100 stellar radii or less.
3. The position angle of the linear polarization shows a characteristic swing (associated with magnetic field line planes).
4. 

The polarization of radio waves is perpendicular to the planes of a dipolar magnetic field.

5. The position angle of highly linearly polarized subpulses follows locally the mean position angle traverse.
6. The orthogonally polarized modes are observed.

Assumptions:

There is an electron-positron plasma moving relativistically along the open magnetic field lines.

The distribution function of the relativistic electron-positron plasma should look like this:

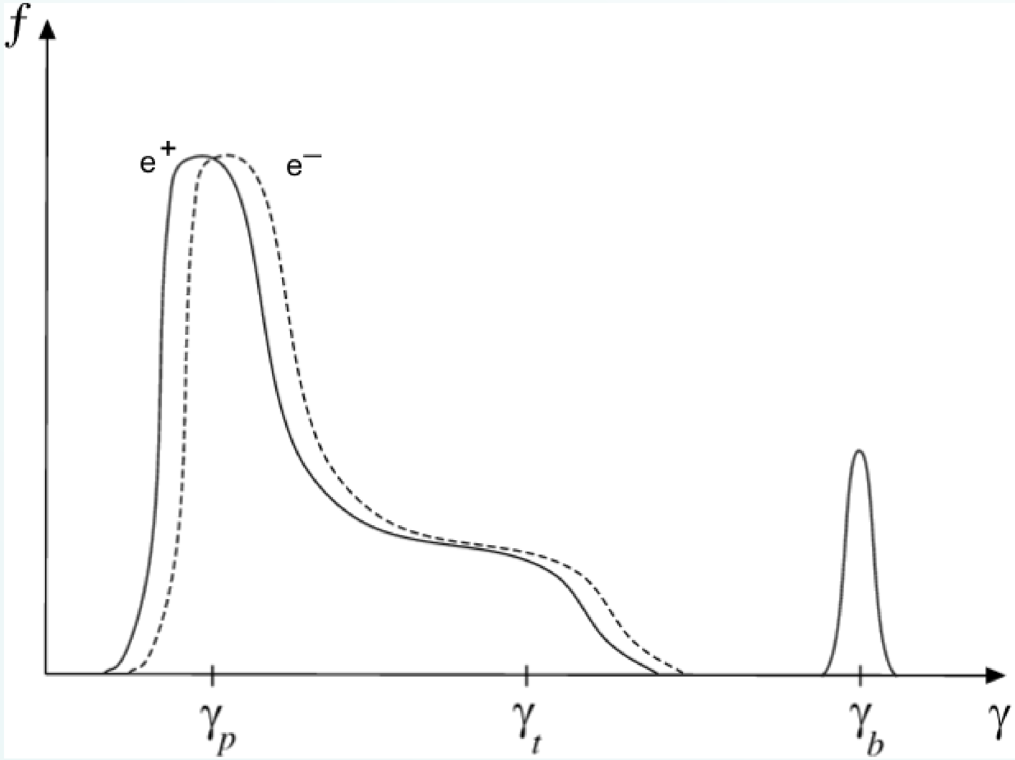
$$n_b \approx n_{GJ}$$

$$n_b \gamma_b \approx \frac{1}{2} n_p \gamma_p$$

$$\frac{n_p}{n_b} \approx \kappa \approx 10^2 - 10^4$$

$$\gamma_p \approx 10^2 - 10^3$$

$$\gamma_b \approx 10^5 - 10^6$$



The plasma is strongly magnetized.

$$\frac{\omega_p^2}{\tilde{\omega}_B^2} = \left(\frac{\omega_p^2}{\tilde{\omega}_B^2}\right)_0 \left(\frac{R_*}{R}\right)^{-3} << 1$$

$$\omega_p^2 = \frac{4\pi e^2 n_p}{m_e} \qquad \tilde{\omega}_B = \frac{eB}{\gamma m_e c}$$

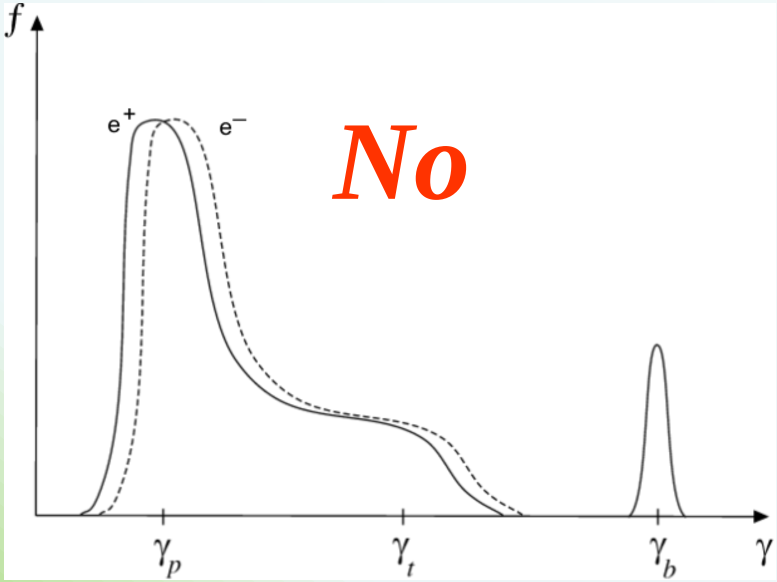
Thus the coherent radio emission of pulsars should be generated by means of some instabilities in the strongly magnetized relativistic electron-positron plasma

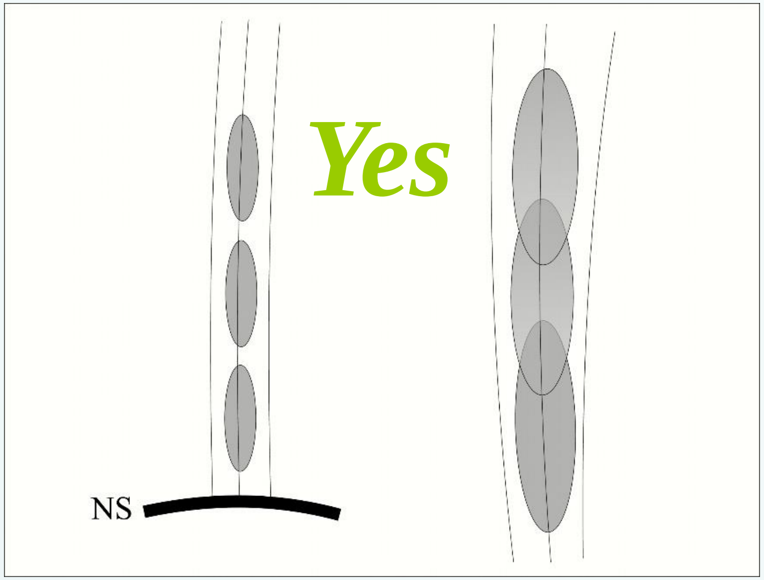
At the altitudes about 100 stellar radii or less the only instability that can arise in the magnetospheric plasma is the two-stream instability.

The two-stream instability is triggered by the relative motion of two species of particles.

Due to the relativistic beam.

Due to the non-stationary sparking discharge (PSG).





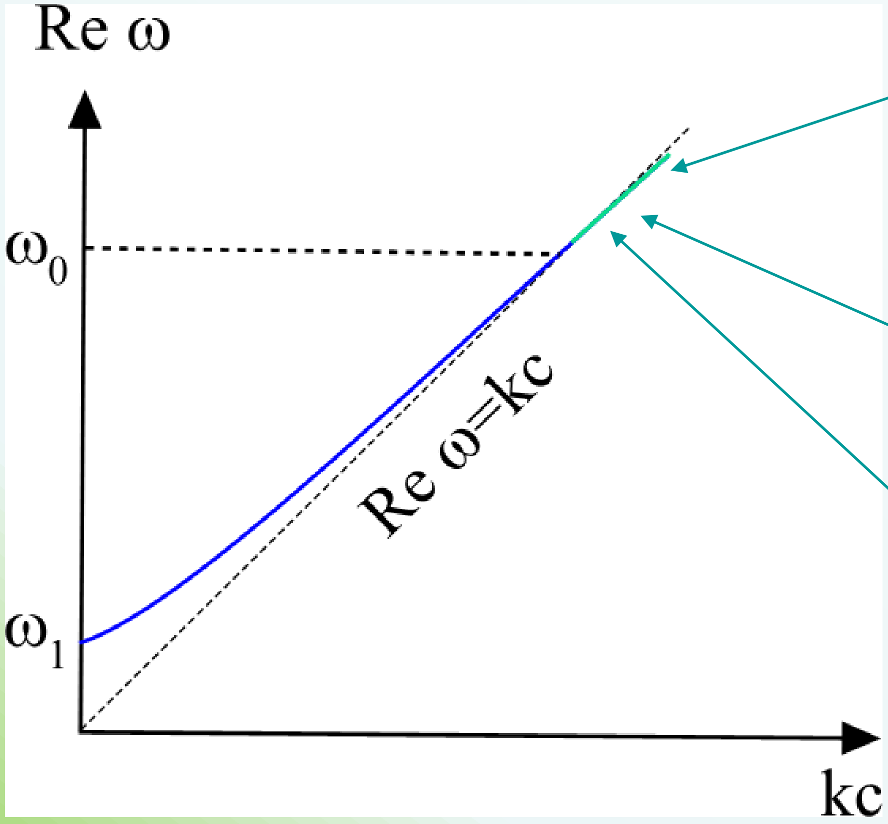
Egorenkov, Lominadze, Mamradz, 1983, Astrophysics, 19, 426.

Usov, 1987, ApJ, 320, 333
Asseo & Melikidze , 1998, MNRAS, 299, 51.

The two-stream instability generates Langmuir waves.

$$\omega_0 = k_0 c = 2\gamma_p^{1/2}\omega_p$$

The resonance condition



$$\boxed{\omega - kv = 0}$$

$$v_f = \frac{\omega}{k}$$

$$v_f \approx c, v_f < c$$

$$v_g = \frac{\partial \omega}{\partial k}$$

$$v_g \approx c, v_g < c$$

$$\omega_1 = \gamma_p^{-3/2}\omega_p$$

But the longitudinal waves cannot leave the magnetosphere.

Thus they cannot explain the radio emission.

We need some process which is triggered by the Langmuir waves and results the radio emission.

The first attempt – Coherent curvature radiation by the linear waves (RS75)

Unsuccessful:

The timescale of the radiative process must be significantly shorter than the plasma oscillation period

$$\omega_r > \omega_0$$

The linear characteristic dimension of bunches must be shorter than the wavelength of radiated wave

$$k_r < k_0$$

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But $\omega_r \approx k_r c$ *and* $\omega_0 \approx k_0 c$

It is impossible to satisfy simultaneously the above two conditions!

The nonlinear theory

The Langmuir waves are modulationally unstable, and their nonlinear evolution results in formation of plasma solitons.

The nonlinear Schrödinger equation.

$$i\frac{\partial}{\partial\tau}E_{\parallel}^{(1)} + G\frac{\partial^2}{\partial\xi^2}E_{\parallel}^{(1)} + q\left|E_{\parallel}^{(1)}\right|^2 E_{\parallel}^{(1)} + s\frac{1}{\pi}\oint\frac{\left|E_{\parallel}^{(1)}(\xi',\tau)\right|^2}{\xi-\xi'}d\xi' E_{\parallel}^{(1)} = 0.$$

The Langmuir soliton

$$E_{\parallel}^{(1)}(\xi,\tau) = E_{\parallel o}^{(1)}\mathrm{sech}\left(E_{\parallel o}^{(1)}\sqrt{\frac{q}{2G}}(\xi-u\tau)\right)\exp\left\{i\left(\frac{u}{2G}\xi - \frac{u^2}{4G}\tau + \frac{1}{2}q\tau\left(E_{\parallel o}^{(1)}\right)^2\right)\right\}$$

Pataraya & Melikidze, 1980, Ap&SS, 68, 61;
Melikidze & Pataraia, 1984, Astrophysics, 20,100;
Melikidze, Gil & Pataraya , 2000, ApJ, 544, 1081.

The corresponding slowly varying charge density

$$\rho' = \frac{\sum_\alpha e_\alpha \omega_{p\alpha}^2 \oint \frac{1}{(v-v_g)} \frac{d}{dp} \left(\frac{(v-v_g)}{(\omega_l - k_l v)^2} \frac{df_\alpha}{dp} \right) dp}{4\pi \sum_\alpha \omega_{p\alpha}^2 \oint \frac{1}{(v-v_g)} \frac{df_\alpha}{dp} dp} \times \frac{\partial^2}{\partial \xi^2} \mid E_\parallel^{(1)} \mid^2$$

The charge distribution within the envelope soliton is proportional to e_α^3

Thus if the distribution functions of both species of particles (electrons and positrons) are the same: $\rho' = 0$

Otherwise the charge density changes sign and it can be modeled as a system of three charges.

Melikidze & Pataraia, 1984, Astrophysics, 16,100;
Melikidze, Gil & Pataraya , 2000, ApJ, 544, 1081.

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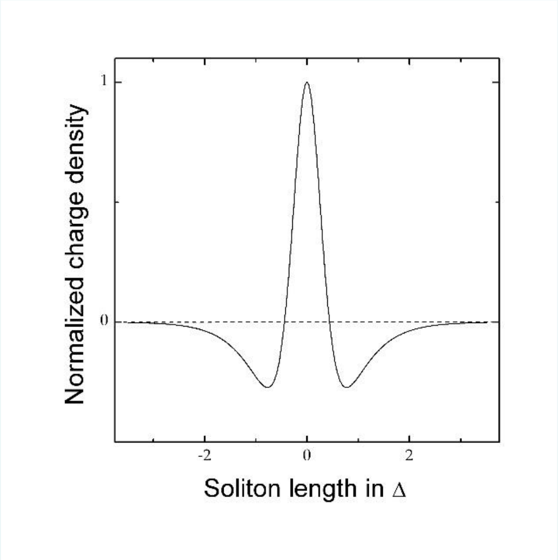
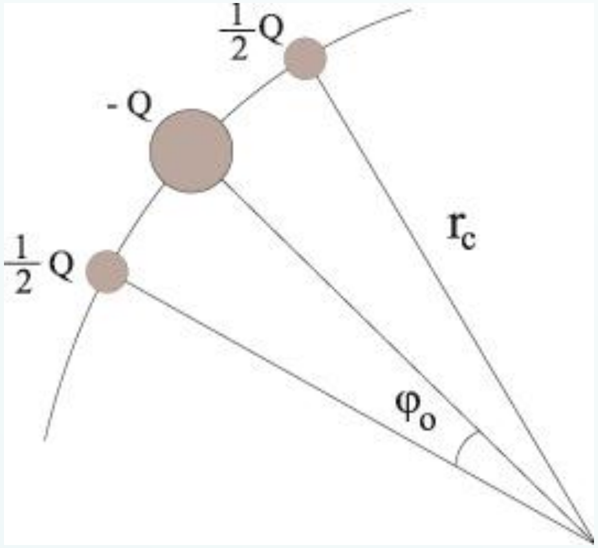


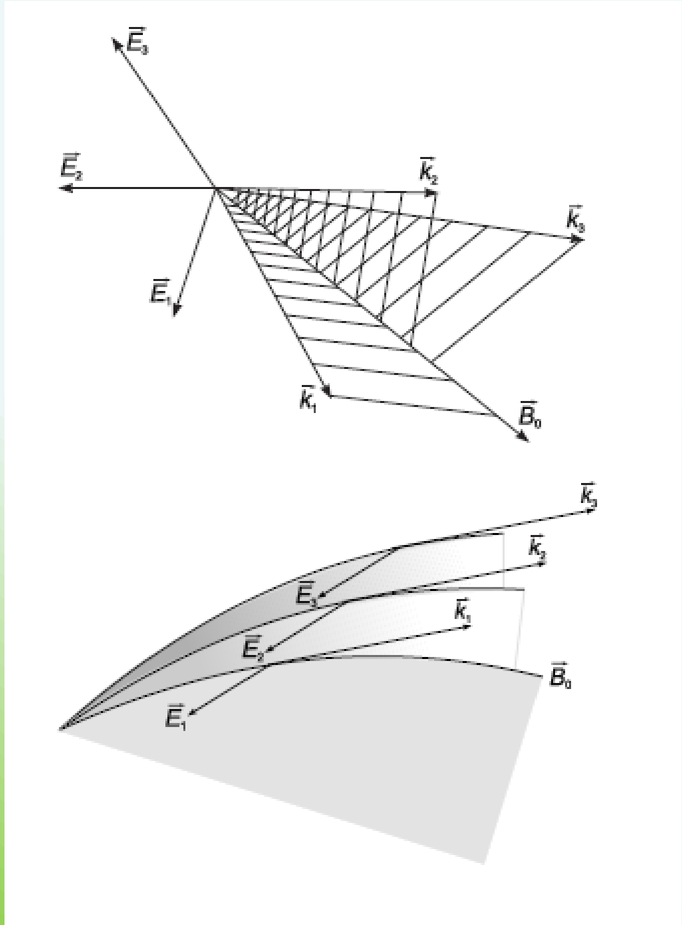


Such a system is capable of emitting the coherent radio emission on the frequencies well below the characteristic plasma frequency: $\omega_r << \omega_0$

Melikidze & Pataraia, 1984, Astrophysics, 16,100;
Melikidze, Gil & Pataraya , 2000, ApJ, 544, 1081.

The curvature radiation scenario well satisfies the observations.

Position angle of the highly linearly polarized subpulses is orthogonal to the surface of the curved dipolar magnetic field lines.



Mitra, Gil & Melikidze, 2009, *ApJ*, 696, L141
Gil, Lyubarsky, Melikidze, 2003, *ApJ*, 600,878

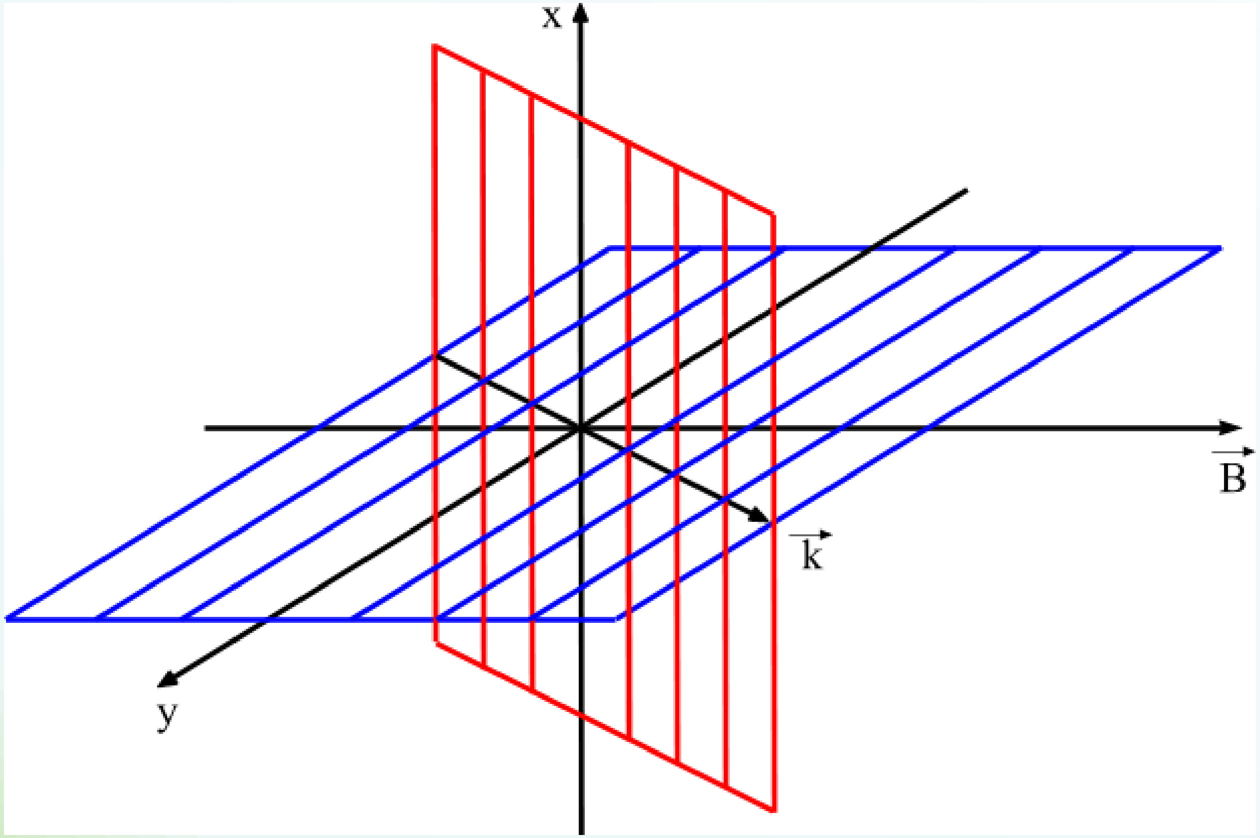
Such a feature can be explained only by the extraordinary waves generated by the curvature radiation!

The curvature mechanism is the only mechanism which distinguishes the plane of the curved field lines.

Polarization of waves in the magnetized pair plasma

Purely electromagnetic

Longitudinal-transverse

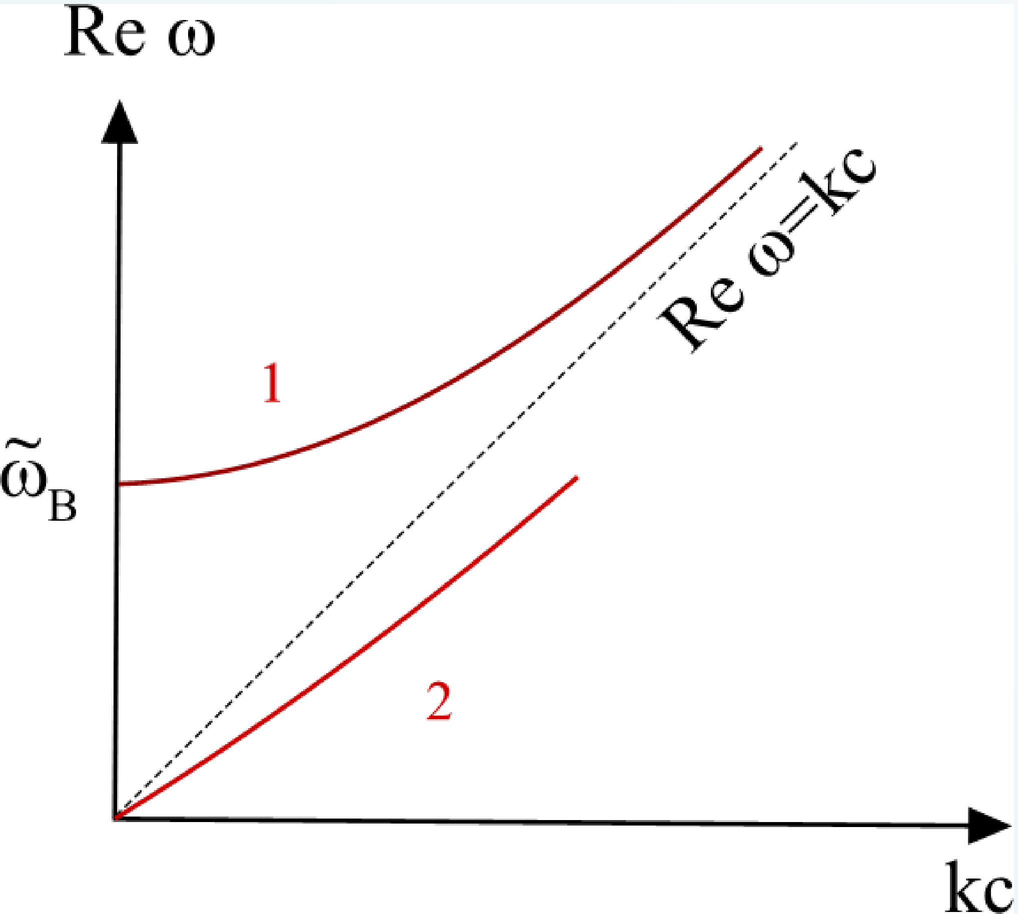


Spectra of the extraordinary waves

1 – High-frequency wave.

$$\omega_X = kc(1-\delta)$$

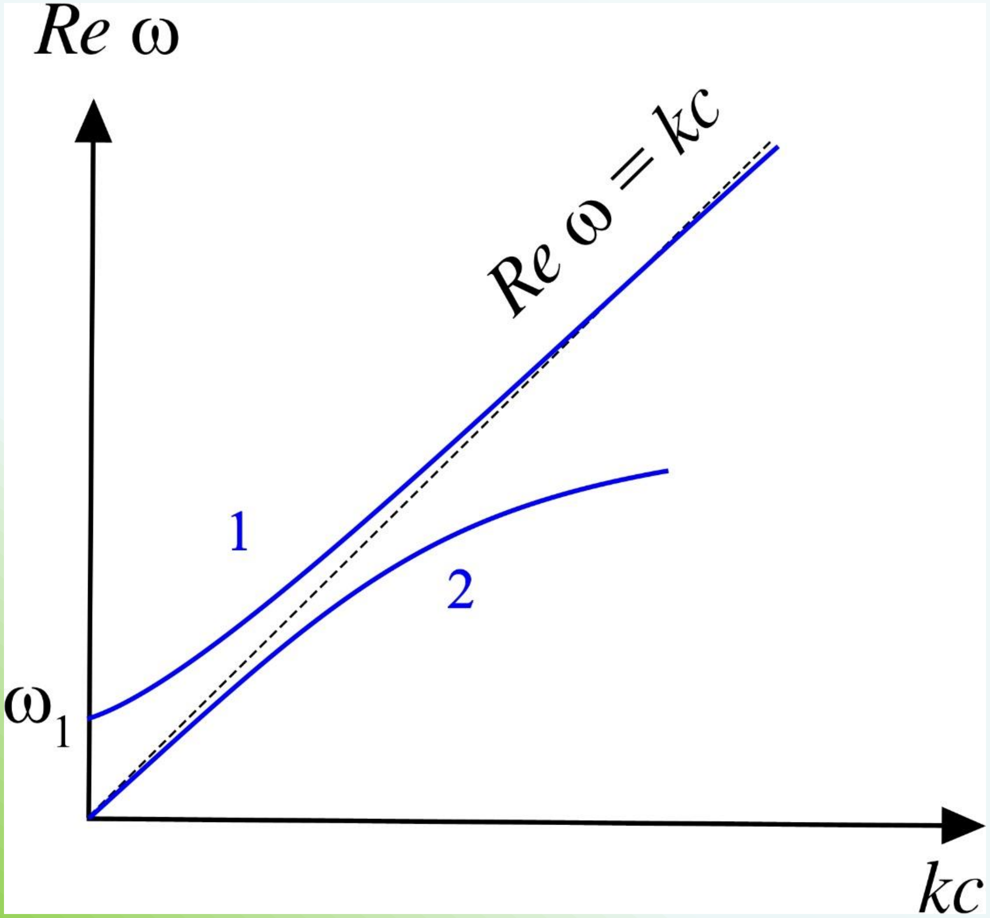
$$\delta \approx \frac{1}{4}\frac{1}{\gamma^3}\frac{\omega_p^2}{\omega_B^2}$$



2 – Low-frequency t-wave: extra-ordinary mode.

2 – The low frequency o-wave.

$$\omega_1 = \gamma_p^{-3/2}\omega_p$$



1 – High frequency L-wave.

The orthogonal mode.

If $k_\perp \neq 0$ *of L-wave in the high-frequency region*

$$\omega \gg \omega_0 = 2\gamma_p^{0.5}\omega_p$$

are almost electromagnetic waves polarized orthogonally to the polarization of t-waves.

The Partially Screened Gap

Positive charges then cannot be supplied at the rate that would compensate the inertial outflow through the light cylinder. As a result, a significant potential drop develops above the polar. The accelerated positrons would leave the acceleration region, while the electrons would bombard the polar cap surface, causing a thermal ejection of ions, which are otherwise more likely bound in the surface in the absence of additional heating. This thermal ejection would cause partial screening of the acceleration potential drop corresponding to a screening factor:

$$\Delta V = \eta \frac{2\pi}{cP} B_s H^2$$

The screening factor

In neutron stars with positively charged polar caps the outflow of iron ions is limited by thermionic emission and determined by the surface-binding (cohesive) energy. Following the results of Cheng & Ruderman, (1980, ApJ, 235, 576) we are considering a general case of a pulsar inner accelerator in the form of a charge depletion region rather than a pure vacuum gap. The outflow of iron ions can be described in the form

$$\frac{\rho_i}{\rho_{GJ}} \approx \exp\left(30 - \frac{\varepsilon_c}{kT_s}\right)$$

The surface-binding (cohesive) energy

$$\eta = 1 - \frac{\rho_i}{\rho_{GJ}} = 1 - \exp\left[30\left(1 - \frac{T_i}{T_s}\right)\right]$$

$$T_i = \frac{\varepsilon_c}{30k}$$

The shielding factor

The critical temperature

Because of the exponential sensitivity of the accelerating potential drop ΔV to the surface temperature T_s, the actual potential drop should be thermo-statically regulated. In fact, when ΔV is large enough to ignite the cascading pair production, the back-flowing relativistic charges will deposit their kinetic energy in the polar cap surface and heat it at a predictable rate. This heating will induce thermionic emission from the surface, which will in turn decrease the potential drop that caused the thermionic emission in the first place. As a result of these two oppositely directed tendencies, the quasi-equilibrium state should be established, in which heating due to electron bombardment is balanced by cooling due to thermal radiation. This should occur at a temperature T_s slightly lower than the critical temperature above which the polar cap surface delivers thermionic flow at the corotational charge density level.

The quasi-equilibrium condition is

$$\sigma T_s^4 = \gamma m_e c^3 n$$

where $$\gamma = {e\Delta V}\Big/{m_e c^2}$$

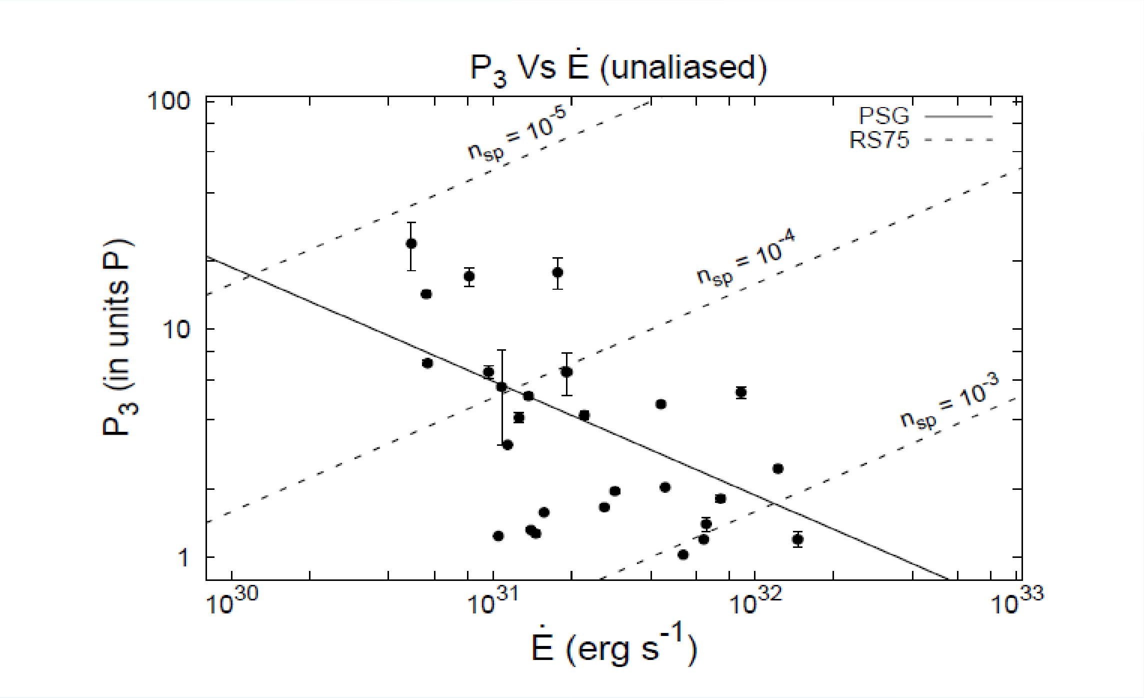
and $$n = n_{\mathrm{GJ}} - n_i = \eta n_{\mathrm{GJ}}$$

$$T_s = 1.4\times10^6 \left(\frac{B_s}{10^{14}\,\mathrm{G}}\right)^{0.5} \left(\frac{H}{10^3\,\mathrm{cm}}\right)^{0.5} \left(\frac{\eta}{10^{-2}}\right)^{0.5} \left(\frac{P}{1\mathrm{s}}\right)^{-0.5} \mathrm{K}$$

Partially Screened Gap (PSG model)

1. *Positive charges cannot be supplied at the rate that would compensate the inertial outflow through the light cylinder. As a result, significant potential drop develops above the polar.*
2. *Back-flow of electrons heats the surface to temperature above 10^6 K.*
3. *Thermal ejection of iron ions causes a partial screening of the acceleration potential drop.*
4. *Consequently, backflow heating decreases as well.*
5. *Thus heating leads to cooling – this is a classical thermostat.*
6. *Surface temperature T_s is thermostatically regulated to retain its value close to critical temperature T_i above which thermal ion flow reaches co-rotation limited level (Goldreich-Julian charge density)*
7. *According to calculations of cohesive energy by Medin-Lai (2007), this can occur if the surface magnetic field is close to 10^{14} G. In majority of radio pulsars this has to be highly non-dipolar crust anchored field.*

P_3 of the pulsars showing the phase modulated drifting as a function of $\dot{E}$.



The PSG model – solid line $P_3 \propto \dot{E}^{-0.5}$

The Ruderman-Sutherland (RS75) model – dashed lines.

In the PSG model $P_3 = \frac{1}{2\pi\cos(\alpha)}\frac{1}{\eta}$ $\eta = 1 - {}^{n_i}/{}_{n_{GJ}}$

The full energy outflow from the polar cap can be expressed as

$$L_{\mathrm{PSG}} \approx \gamma_0 m_e c^3 \eta n_{\mathrm{GJ}} A_{\mathrm{pc}}$$

γ_0 *is a characteristic Lorentz factor of electrons or positrons accelerated in the gap.*

$n_{GJ}A_{pc}$ *does not depend on the surface magnetic field configuration.*

The ratio of L_{PSG} *and* $\dot{E}$ *can be estimated as*

$$\xi = \frac{L_{\mathrm{PSG}}}{\dot{E}} \approx 5.7 \times 10^{-8} \eta \gamma_0 \cos(\alpha) \left(\frac{\dot{P}}{P^3}\right)^{-0.5}$$

Therefore $P_3 \approx 10^{-8} \left(\frac{\gamma_0}{\xi}\right) \left(\frac{P^3}{\dot{P}}\right)^{0.5}$

$\xi \sim 10^{-3}$ - *Becker and Truemper*. $\gamma_0 \sim 10^5 - 10^6$

Thus the PSG model predicts the proper dependence!

Conclusion:

1. *The sparking discharge provides the necessary conditions for the two stream instability.*
2. *The Langmuir turbulence creates and supports charged bunches.*
3. *Features of the coherent curvature radiation in the magnetized electron-positron plasma naturally explains the observed features of the radio emission.*
4. *The PSG model predicts the proper value for the velocity of the drifting subpulses.*

Thank you!